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Conformal Dielectric-Filled Edge-Slot Antennas for Bodies of Revolution

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A class of circumferential-slot antennas that are ideally suited for conformal mounting on conducting bodies of revolution has been developed. The simplest form of the antenna is a disk of dielectric substrate that is copper-plated on both sides and mounted between two parts of the conducting body so that the aperture coincides with the surface. The antenna is excited by a single coaxial stub at the center and is tuned for proper

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operating frequency by inductive posts that connect the two copper-plated sides of the disk. By varying the number and location of the inductive posts, the operating frequency of a single antenna can be tuned over a six-to-one range. In practice, plated-through holes are used as inductive posts in order to provide mounting and access holes. The single coaxial feed excites azimuthally symmetric fields that are not significantly distorted by the symmetrically placed inductive posts. Therefore, radiation patterns of edge-slot excited bodies display a high degree of azimuthal symmetry. The small size, light weight and inexpensive fabrication procedure make the edge-slot attractive for many applications.

CONTENTS

FIGURES

FIGURES (Cont'd)

1. INTRODUCTION

To help meet the continuing need for small, rugged, lightweight, conformal antennas for bodies of revolution, a class of circumferential-slot antennas, called edge-slot antennas, has been developed. The edge-slot antennas are filled with a low-loss dielectric material that provides structural strength and reduces the size of the antennas relative to the free-space wavelength. The antennas are simple and inexpensive to manufacture and they are rugged enough to operate in a ballistic environment. The edge-slot antenna is excited by a single coaxial feed and is symmetrically constructed in order to radiate uniformly in the azimuthal plane. The basic, planar edge-slot antenna occupies a minimum of space at the surface of the body and, for certain applications, is better than cavity-backed slot, microstrip or patch antennas. A modified version of the antenna, a conical edge-slot antenna, is excellent for use on the nose cone of a projectile.

A number of edge-slot antennas have been constructed and tested and numerous curves relating the physical and electrical characteristics have been obtained. The operating frequency and input impedance of the antenna are most affected by the configuration of the antenna itself, but the radiation pattern is strongly influenced by the external body.

2. BASIC EDGE-SLOT ANTENNA

The basic, two-element edge-slot antenna, depicted in figure 1, consists of a thin disk of dielectric material that is copperplated on both sides and excited by a single coaxial stub at the center.

Rows of diametrically opposed inductive posts separate the antenna into two radiating elements. The posts, which connect the copperplated sides of the antenna, also tune the operating frequency and impedance of the antenna. In practice, plated-through holes are often used instead of solid posts to facilitate construction and to reduce the weight. The holes are used also for mounting and for passing electrical cables and structural supports through the antenna. Because azimuthally symmetric radiation patterns are desired, the inductive posts are placed symmetrically about the center of the disk. The rows of posts on each side of the feed in figure 1 divide the antenna into identical segments that are excited equally and in phase by the central feed region. Examples of two-element, four-element and eight-element edge-slot antennas are shown in figure 2.

When used in conjunction with typical weapon systems, the edge-slot antenna can be mounted conformally between portions of a conducting body of revolution. Because the aperture is very narrow and because it couples strongly to the body, full advantage can be taken of the

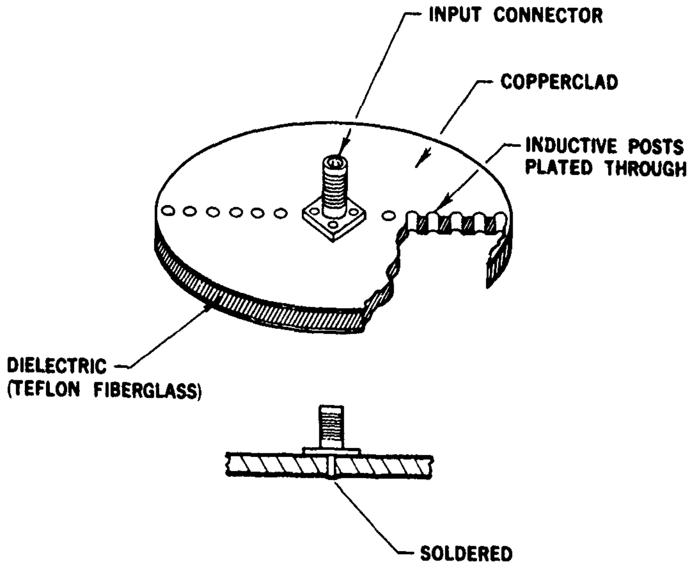

Figure 1. Two-element edge-slot antenna.

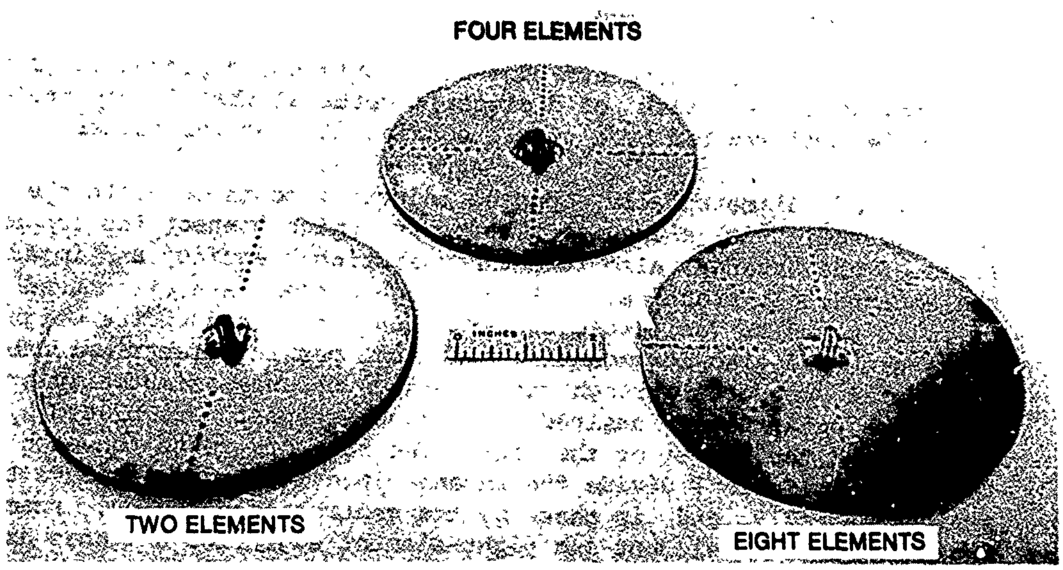

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Figure 2. Typical two-element, four-element, and eight-element edge-slot antennas constructed of 3.18-mm (1/8-in.) copper-plated Teflon fiberglass with plated-through inductive posts.

radiation properties of the larger structure. Furthermore, the rotational symmetry of the antenna and the body preserve the desired azimuthal symmetry of the radiation pattern.

The edge-slot antenna is ideally suited for mounting on bodies that are compartmentalized because it provides a natural boundary, complete with mounting and access holes, between the portions of the body. Electronic components in one compartment can be electromagnetically isolated from components in the other compartment. Also, because only the thin aperture extends to the surface, disruption of structural and aerodynamic features of the exterior surface is minimal. The disruption is minimal especially if the antenna is mounted at a natural junction of the body, which is the case in many weapon systems.

3. OPERATING CHARACTERISTICS

Unlike the radiation characteristics, which are strongly affected by the external body, the input terminal characteristics (operating frequency and impedance) of the edge-slot antenna are strongly affected by the number and locations of the inductive tuning posts. The posts contribute significantly to the impedance match of the antenna and are used to minimize the VSWR at the desired operating frequency. No external network is needed to match the edge-slot antenna to a standard 50-ohm generator. Figure 3 shows the variations in operating frequency, defined by minimum VSWR, with the number of posts for a two-element

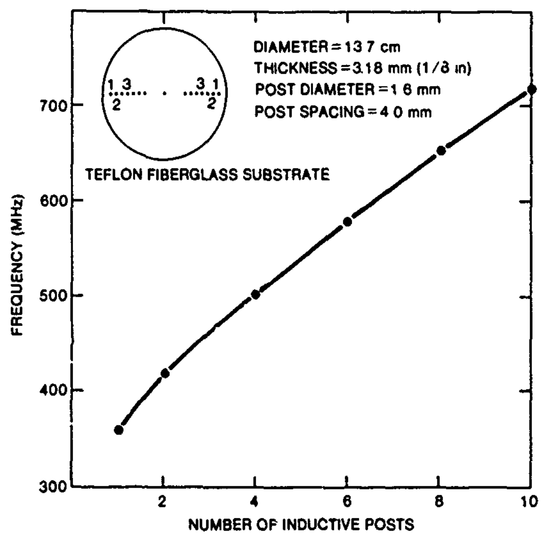

Figure 3. Operating frequency versus number of inductive posts for two-element antenna. Data taken with antenna mounted at center of conducting cylinder 13.7 cm in diameter and 27.4 cm long.

edge-slot antenna. The posts are inserted symmetrically so that the number "1" actually implies two posts. The two-element antenna can be tuned from 360 to 720 MHz without changing its fundamental dimensions.

Removal of the number 1 posts from the two-element antenna in figure 3 does not give an operating frequency below 360 MHz. At least one pair of posts is necessary for proper operation of the antenna. The only known way to further lower the frequency (for a fixed dielectric constant) is to increase the diameter of the antenna.

The effect of increasing the number of elements is shown in figure 4. With the number of posts separating the elements held constant at nine, the operating frequency increases from 720 to 2315 MHz as the number of elements increases from two to eight. Figures 3 and 4 show that a single edge-slot antenna can be tuned over a six-to-one frequency range. The disk diameter is $0.16\lambda_0$ at 360 MHz and $1.08\lambda_0$ at 2315 MHz (λ_0 = free space wavelength). The data of figures 3 and 4 were obtained with the antenna mounted in the center of a 27.4-cm-long cylinder.

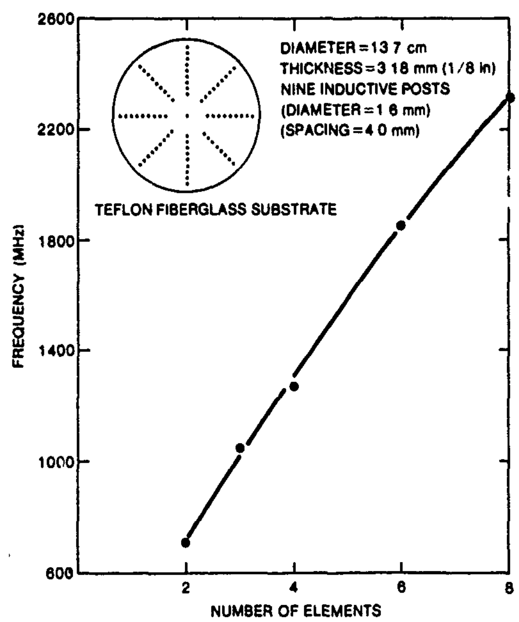

Figure 4. Operating frequency versus number of elements with nine inductive posts separating elements. Antenna was mounted at center of 27.4-cm-long cylinder.

The bandwidth and VSWR of the antenna depend on the configuration of the antenna, the body on which it is mounted and the operating frequency. The bandwidth (VSWR $\leq$ 2) of the two-element antenna mounted at the center of the 27.4-cm-long cylinder was typically 3 percent but considerably greater bandwidths have been observed for other antennas and bodies.

The dramatic tuning of the antenna displayed in figures 3 and 4 was accomplished by continually increasing the number of inductive posts. A less pronounced tuning can be accomplished by varying the location or size or both of a fixed number of posts. Figure 5 shows the changes in operating frequency as two posts are moved from the edge of the antenna toward the center. Also shown is the increase in operating frequnency with increasing post diameter.

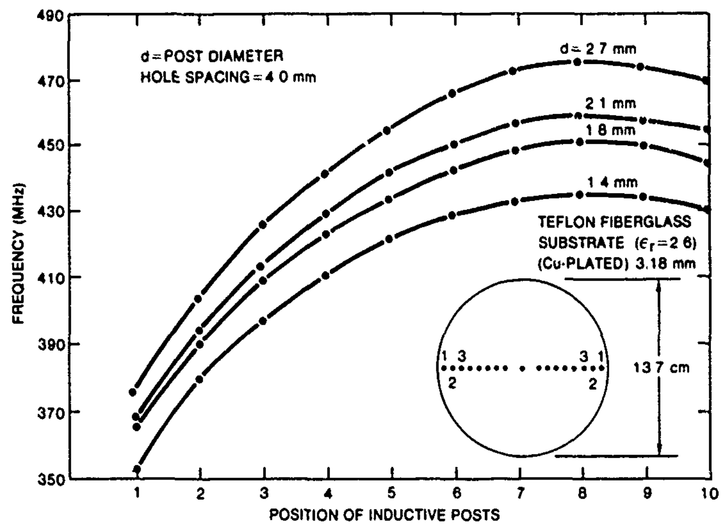

Figure 5. Effects of post position and diamter on operating frequency of two-element antenna. Single pair of posts is moved from edge toward center.

The radiation pattern of the edge-slot antenna is strongly influenced by the body on which it is mounted. This influence can be seen in the far-field radiation patterns of figures 6 and 7, which were taken with the antenna mounted at the center of the 27.4-cm-long cylinder. The patterns on the left were taken in the plane of the edge-slot antenna (θ = 90 deg) and those on the right were taken in a plane perpendicular to the antenna (ϕ = 0 deg). The radiation is nearly uniform in the θ = 90-deg plane and is similar to a dipole in the ϕ = 0-deg plane. The cylinder is $0.33\lambda_0$ long at 360 MHz and $2.17\lambda_0$ long at 2315 MHz. Absolute gains varied from 1 dB at 360 MHz to 6 dB at 2315 MHz.

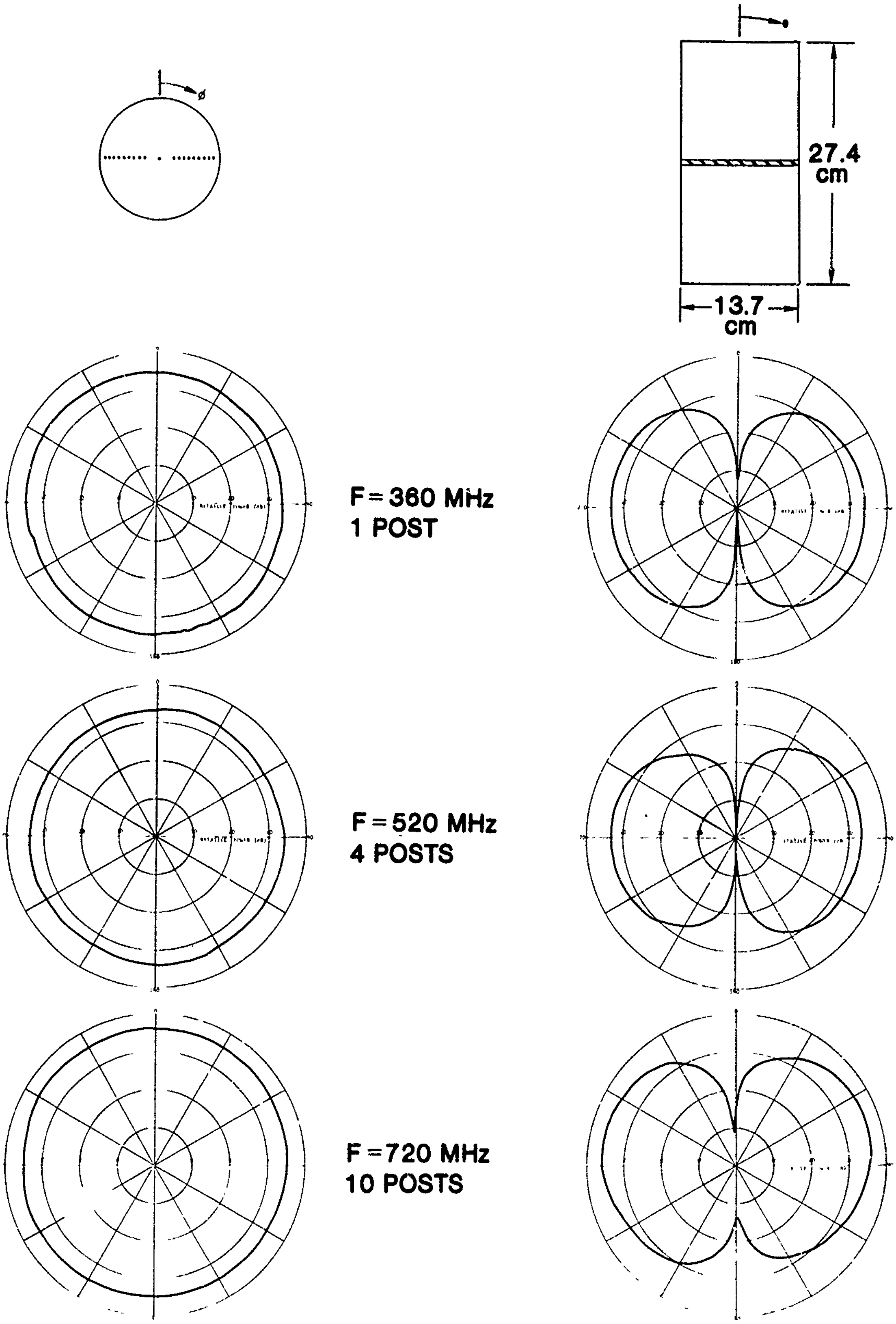

Figure 6. Radiation patterns of two-element edge-slot antenna mounted at center of 27.4-cm-long cylinder.

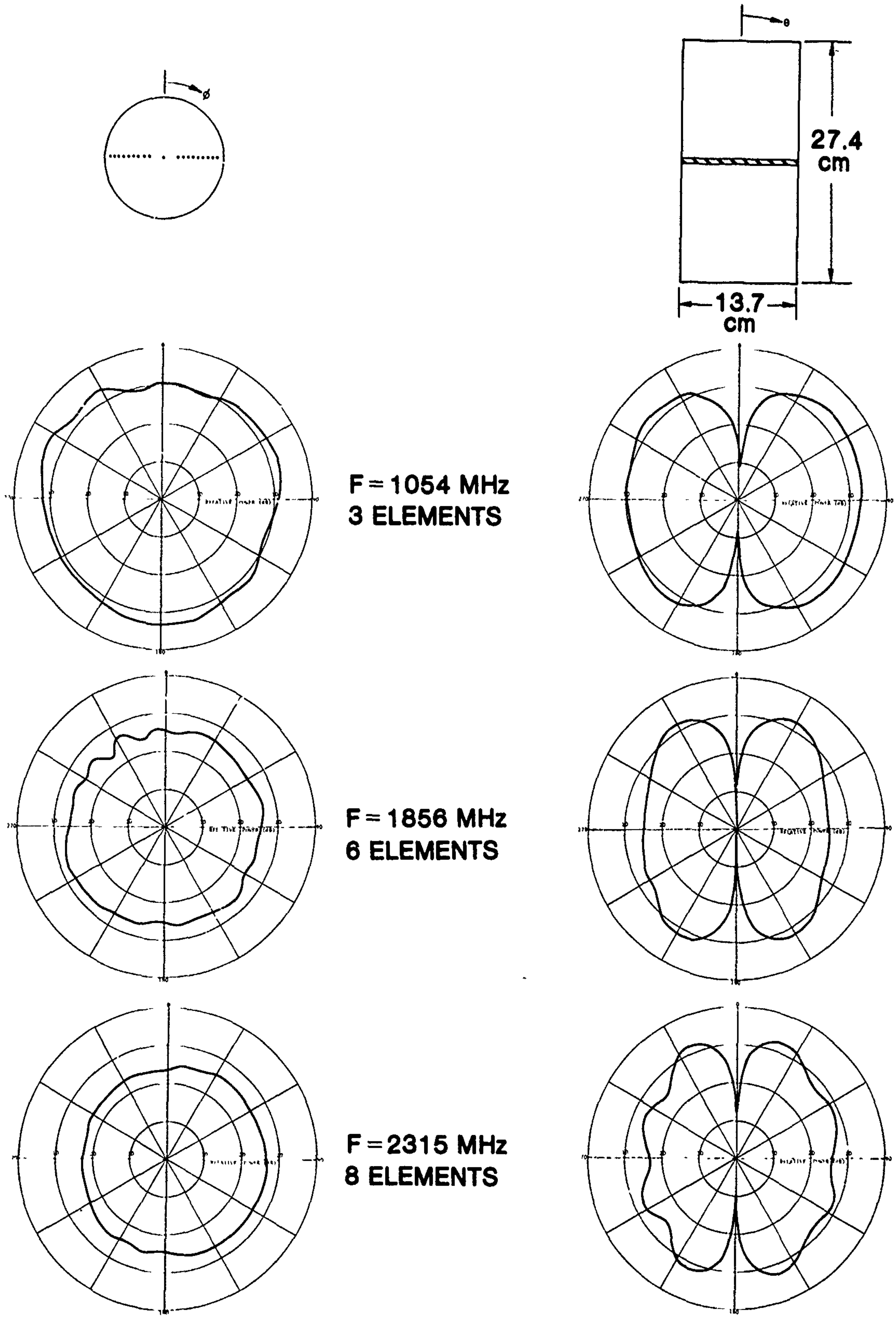

Figure 7. Radiation patterns of multielement edge-slot antennas mounted at center of 27.4-cm-long cylinder.

4. ANTENNAS OF OTHER DIAMETERS

In order to cover other operating bands, edge-slot antennas having diameters of 4.0, 7.6, and 20.3 cm have been built and tested. Their operating characteristics, which are similar to those described in section 3, are summarized in this section. All the antennas described here were constructed of 3.18-mm (1/8-in.) Teflon fiberglass substrate.

The 20.3-cm-diameter antenna was found to operate over frequency ranges of 220 to 500 MHz (two elements) and 355 to 860 MHz (four elements). Data taken with the antenna mounted at the center of a 40.6-cm-long cylinder are shown in figure 8. Typical radiation patterns of the four-element edge-slot antenna mounted at the center of the 40.6-cm-long cylinder are shown in figure 9.

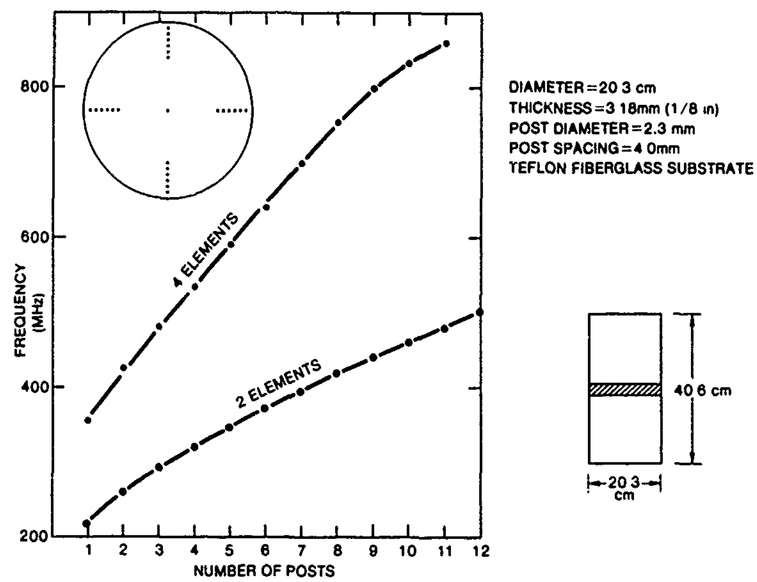

Figure 8. Operating frequencies of 20.3-cm diameter antenna mounted at center of 40.6-cm-long cylinder.

Two-element, four-element and six-element models of the 7.6-cm-diameter antenna were found to operate over frequency ranges of 660 to 1210, 1070 to 2230 and 1350 to 3080 MHz, respectively. Figure 10 shows the operating frequency curves for the antenna mounted at the center of a 15.2-cm-long cylinder. Typical radiation patterns for the 7.6-cm-diameter edge-slot antenna, mounted on the cylinder, are shown in figure 11.

Operating frequencies of the 4.0-cm-diameter antenna are shown in figure 12. An eight-element version of this antenna has also been built

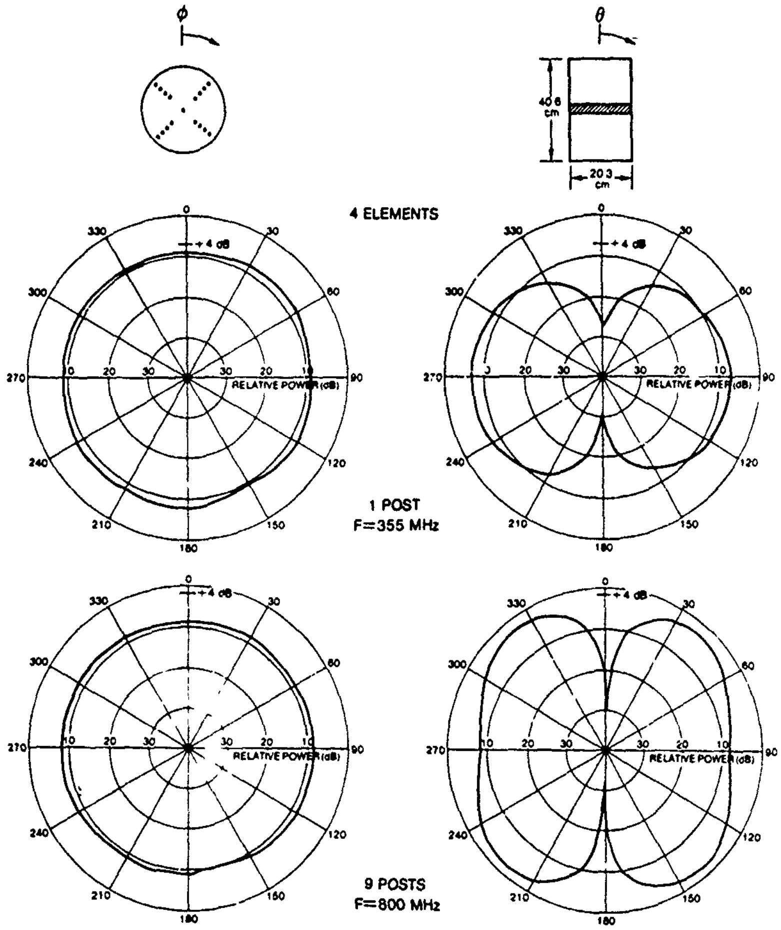

Figure 9. Radiation patterns of 20.3-cm edge-slot antenna mounted at center of 40.6-cm cylinder.

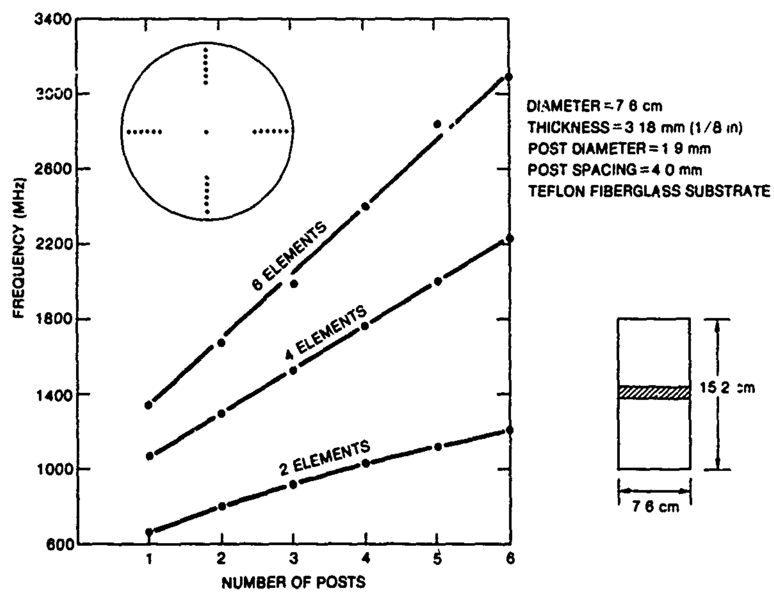

Figure 10. Operating frequencies of 7.6-cm diameter edge-slot antenna mounted at center of 15.2-cm long cylinder.

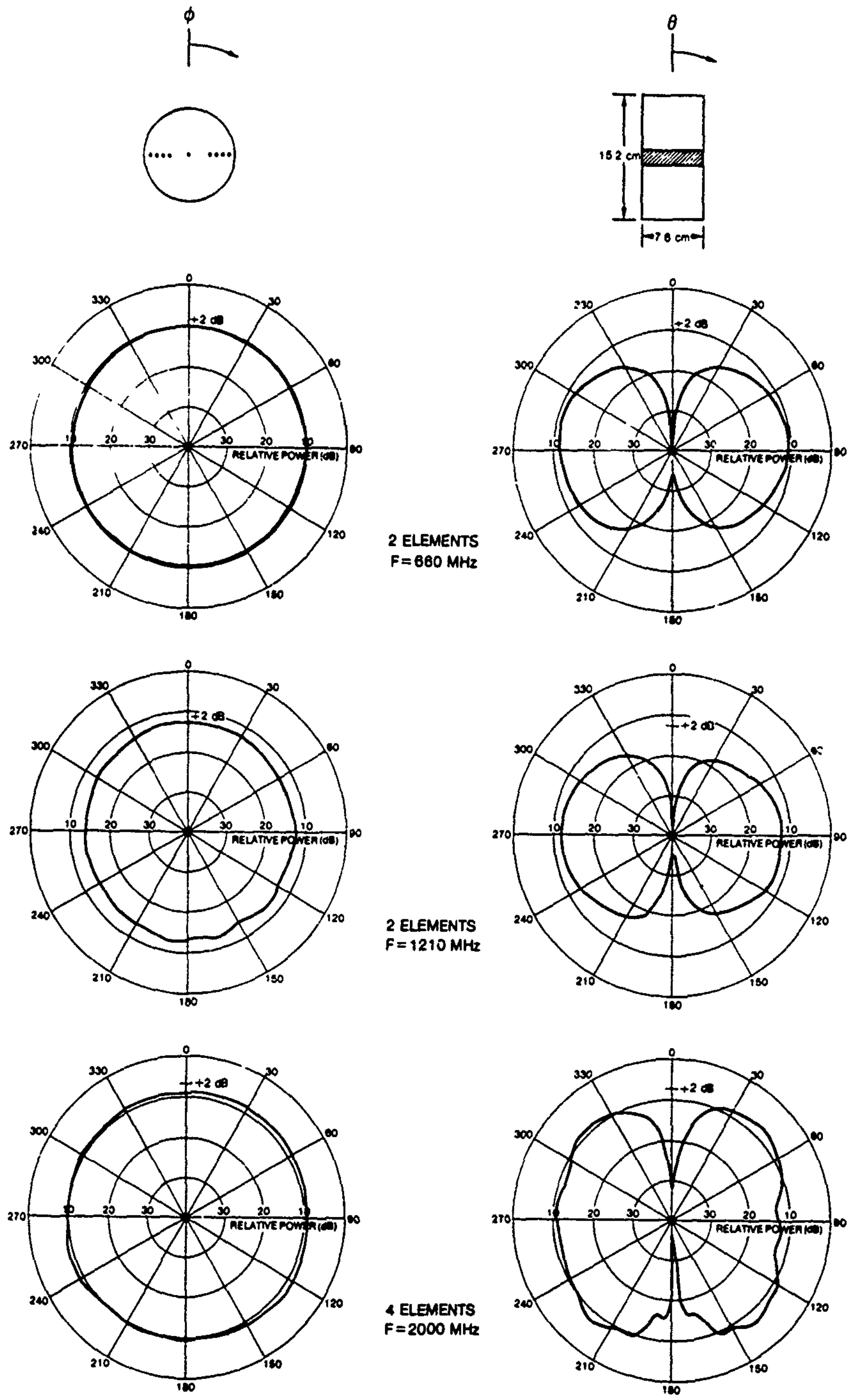

Figure 11. Radiation patterns of 7.6-cm antenna mounted on cylinder.

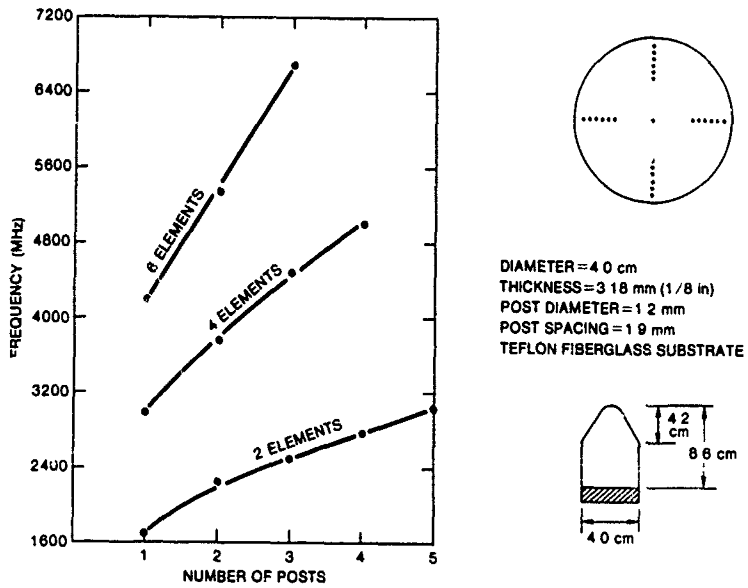

Figure 12. Operating frequencies of 4-cm diameter antenna mounted at the base of 40-mm nose section.

and found to operate at 8300 MHz when three inductive posts are used to separate the elements. Radiation patterns of the four-element edge-slot antenna mounted on a mockup of a 40-mm projectile are shown in figure 13. Once again the azimuthal radiation pattern is symmetric and the elevation radiation pattern (ϕ = 45 deg) is characteristic of the body on which the antenna is mounted.

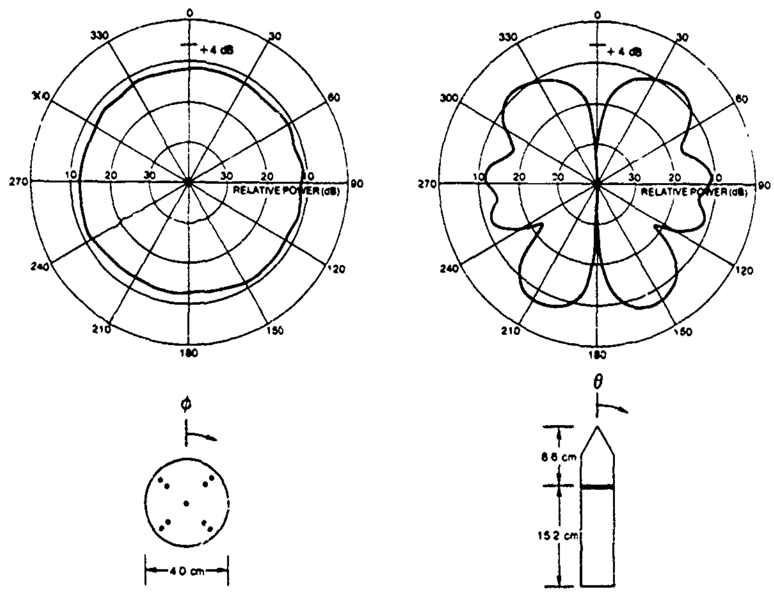

Figure 13. Radiation pattern of four-element edge-slot antenna mounted on mockup of 40-mm projectile.

5. ARRAYS OF EDGE-SLOT ANTENNAS

Many applications involving bodies of revolution require directive beams at a prescribed angle relative to the axis of the body. This requirement can be met easily by using arrays of edge-slot antennas. Because the antenna is a thin disk, the individual radiators can be placed close together without physical interference. Figure 14 shows a mockup of a 40-mm projectile with an array of two edge-slot antennas. Each antenna consists of eight elements and operates at 8300 MHz. The radiation patterns for a single antenna and the two-antenna array (excited in phase and spaced $\lambda_0/2$ apart) are shown in figure 15. The effect of some asymmetries in the antennas is evident in the azimuthal patterns. The impedance bandwidth (VSWR $\leq$ 2) of a single antenna on the 40-mm mockup was 1000 MHz (>12 percent).

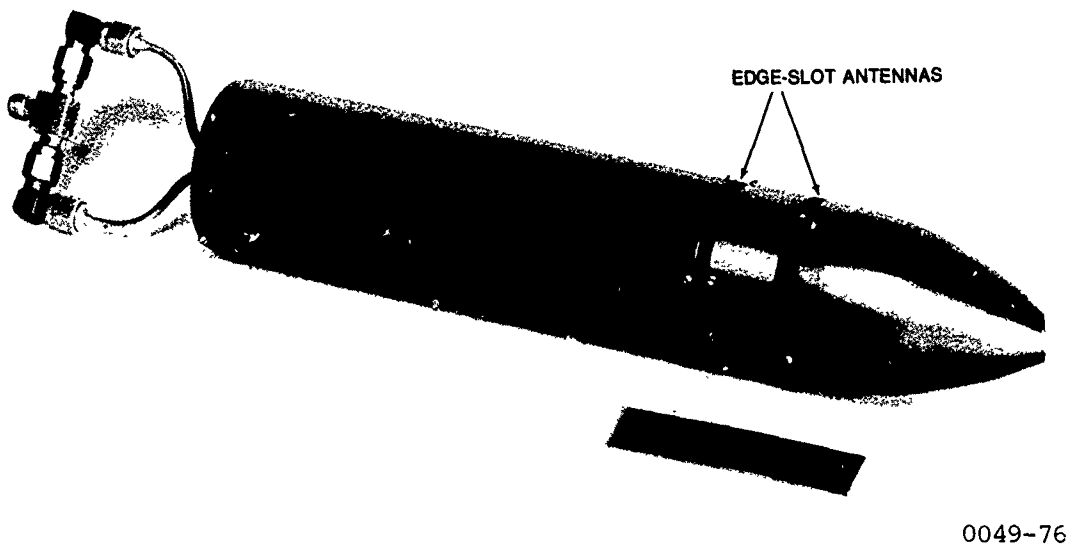

Figure 14. Mockup of 40-mm projectile with array of two edge-slot antennas,

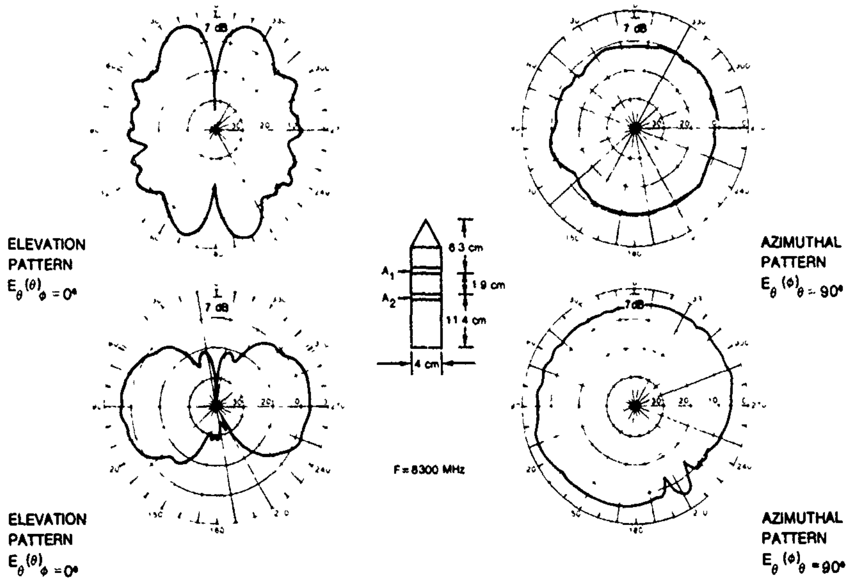

Figure 15. Radiation patterns of single edge-slot antenna (top) and two-antenna array (bottom) mounted on 40-mm projectile.

6. CONICAL GEOMETRY

Sometimes it is not possible to place a flat disk across the body and sometimes the antenna must be mounted near the tip of a conical body where the diameter is not sufficient to build an antenna operating at the desired frequency. In these cases, the planar disk can be deformed (symmetrically) to fit the available space and to operate at the required frequency. An example of a conical edge-slot antenna is shown in figure 16. This four-element antenna forms a hollow nose cone for an 81-mm projectile. The feed is at the tip of the nose cone and the aperture is 3.33 cm back from the tip. Thirteen inductive posts separate the elements and give an operating frequency of 6330 MHz with an impedance bandwidth (VSWR $\leq$ 2) of 150 MHz. Radiation patterns for this conical edge-slot antenna are shown in figure 17. The conical body produces higher gain in the forward quadrant than in the backward quadrant. Also, the azimuthal pattern of this antenna shows a small variation due to the four elements. A radiation pattern for the conical antenna mounted on an 81-mm mortar projectile is shown in figure 18.

The electronic circuitry that feeds the antenna can be housed in the hollow conical compartment inside the antenna. The electronics are then isolated from the radiation fields of the antenna.

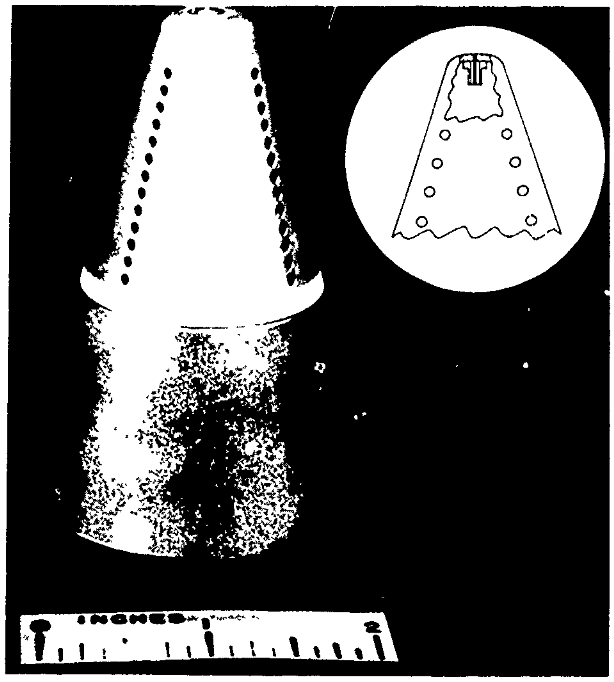

Figure 16. Four-element concial edge-slot antenna.

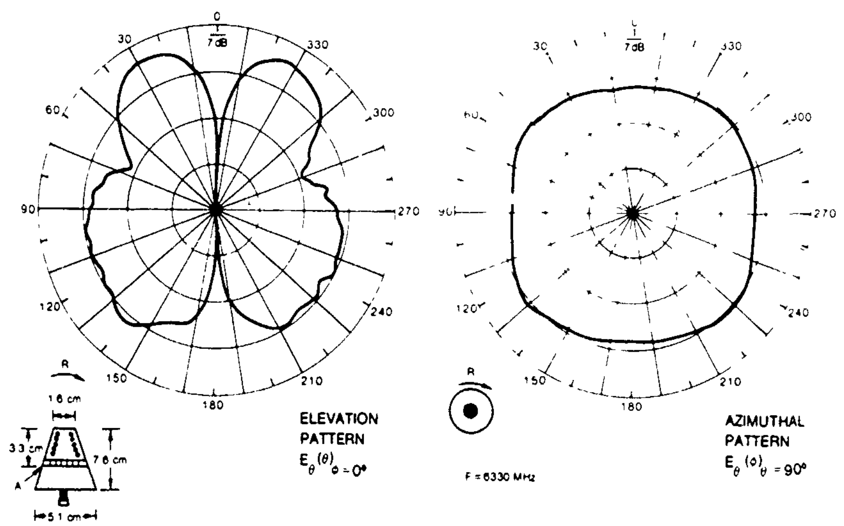

Figure 17. Radiation patterns of four-element conical edge-slot antenna.

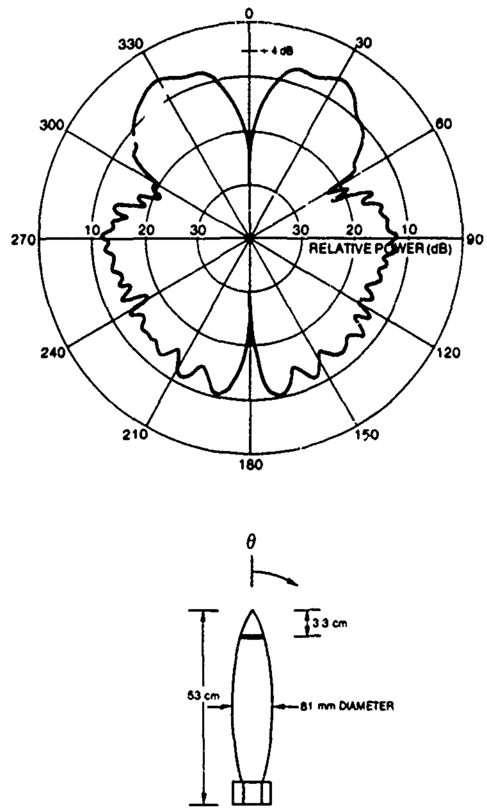

Figure 18. Radiation pattern of conical edge-slot antenna mounted on 81-mm projectile.

7. OTHER OBSERVATIONS AND POSSIBLE EXTENSIONS

The information presented in this report is representative of the large number of data that has been collected on the edge-slot antenna. Several key operating characteristics have been presented, but a number of more subtle characteristics have also been observed. Some of these observations and some possible extensions of the previous work are discussed in this section.

The addition of inductive posts to the edge-slot antenna tunes its operating frequency in discrete steps. The size of these frequency steps is fixed by various design parameters such as the number of elements and the spacing and diameter of the posts. It is, however, possible to tune the antenna to operate between the frequencies presented above by varying the post configuration. For instance, if the four-element antenna described in figure 12 is tuned by alternate rows of two and three inductive posts, an operating frequency of 4140 MHz is achieved. This configuration provides another operating frequency approximately midway between the two-post and three-post frequencies.

Further tuning can be accomplished by removing some of the posts near the edge of the antenna and by changing the post diameter (as shown in fig. 5).

An analytical study of the edge-slot antena is currently underway,* but definitive results are not yet available. However, two empirical models, which explain some of the antenna's behavior, have been developed. The first model is useful for understanding the tuning effect of the inductive posts. The antenna is considered to be a resonant LC circuit: the inductance is due to the current loop from the feed point to the nearest post and back across the opposite surface; the capacitance is due to the conducting surfaces of the antenna. Since the resonant frequency is inversely proportional to the square root of the inductance and of the capacitance, the antenna can be tuned to operate at a higher frequency by reducing the area of the inductive loop (moving the post closer to the feed). Increasing the number of elements places more inductive loops in parallel to lower the effective inductance and, therefore, raise the operating frequency.

The second model recognizes the travelling waves inside the antenna, which resembles a radial transmission line. The rows of inductive posts are considered to form perfectly conducting walls that divide the antenna into radial waveguides of varying lengths and characteristic impedances. By using this model the antenna would operate when the aperture radiation impedance transformed through the radial waveguides to match the generator impedance. The antennas that have been built and tested have mismatch losses of only a few tenths of a decibel at the operating frequency as opposed to greater than 10 dB at frequencies away from resonance. Although a simple first-order analysis† based on this model failed to predict the operating frequencies, the model appears to be useful for understanding the azimuthal symmetry of the radiation patterns. Because the apertures are excited in phase and because their centers are separated by less than $\lambda_o/2$, only the azimuthally symmetric radiation mode is strongly excited.

The above models suggest several variations of the basic edge-slot antenna. Using a higher permittivity substrate should increase the capacitance of the antenna and lower its operating frequency. Using a thicker substrate would create a wider slot aperture and should increase the bandwidth. Also, some of the elements might be eliminated by placing a row of posts or a wall across them at an appropriate distance from the feed point. The unused portion of the element could be removed to provide additional access space or used as an independent radiator.

**The analysis is being performed by the Radiation Laboratory, University of Michigan, under Army Research Office Grant No. DAAG-29-77-G-0152 (Proposal No. 14808-EL).*

†William A. Davis, Single Mode Analysis of the Edge-Slot Antenna, Air Force Institute of Technology (November 1976).

Another interesting phenomenon that has been observed but not investigated is the presence of higher order resonances. That is, an antenna designed to operate at a given frequency operates also at one or more frequencies that are several times greater. This phenomenon might be useful for designing multifrequency antennas. In addition, the antenna could be tuned electronically by replacing the inductive posts with diodes. The bias voltage of each diode would be controlled to provide frequency tuning of the antenna. The gradual transition of the diode impedance from open circuit to short circuit may also permit continuous tuning of the antenna.

8. SUMMARY

The edge-slot antenna has been shown to be a useful radiator for conformal mounting on bodies of revolution. Because it occupies only a narrow ring on the surface of the body, one or a number of edge-slot antennas can be mounted on almost any body contour. By increasing the number of inductive posts separating the elements and by increasing the number of elements, the operating frequency of a single edge-slot antenna can be tuned over at least a six-to-one frequency range. The minimum operating frequency of a given antenna is fixed by its diameter. In order to operate at lower frequencies, the diameter of the antenna must be increased. The criteria that govern the high frequency limit of operation are not yet understood, but the separation of the inductive posts and the angular width of the elements are expected to be limiting factors.

The instantaneous bandwidth of the edge-slot antenna varies somewhat with configuration and operating frequency, but 3 percent is not uncommon for a 3.18-mm-thick antenna operating in the uhf band. Bandwidths of 12 percent have been observed at X band.

A unique feature of the edge-slot antenna is that its radiation pattern in the azimuthal plane is nearly uniform. The inductive posts that tune the antenna do not disrupt the azimuthal summetry of the radiated field.

The construction of the antenna is rugged and simple and the antenna provides a natural boundary when installed between portions of a body. This compartmentalization of the body interior is useful for isolating various electronic circuits. At the same time, the use of plated-through holes for inductive posts provides access between the body portions and holes for fastening the portions together.

The edge-slot antenna is a versatile and useful radiator that can be used for a number of weapon systems. Because the azimuthally symmetric radiation pattern is maintained over a wide range of frequencies, system designers are not restricted in their choices of operating frequencies.

Also, the edge-slot antenna can be integrated into a variety of structures because its shape can be varied to conform to the body and the available space. Further development of the edge-slot antenna is expected to increase the flexibility and reliability and to decrease the size and weight of the antennas used for Army projectiles.

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